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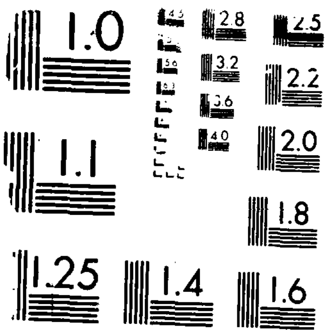

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STUDY OF THE EFFECTS OF METALLURGICAL FACTORS ON THE GROWTH OF FATIGUE MICROCRACKS

FINAL REPORT

James Lankford

November 25, 1987

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Crystallographic and microstructural factors involved in the growth of small fatigue cracks have been characterized for Al alloys. Special techniques have been used to study and quantify the behavior of local crack tip yielding and incremental crack advance. Results have been incorporated into a physically-based, deterministic crack growth model which successfully predicts microcrack growth rates.

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I. Statement of the Problem

This report summarizes the results of a three-year research program aimed at the development of a quantitative crack growth model based on the microstructurally controlled factors responsible for the "anomalous" behavior[1] (i.e., unexpectedly rapid rates of growth) of small fatigue cracks. The modeling effort required the experimental characterization of yielding and crack opening/extension micromechanics within a highly localized region adjacent to the crack tip. This work is tedious and technically difficult, since "small" cracks usually range in size from as small as 5 μm, to no more than ≈200 μm, in length, and the relevant microstructural crack tip behavior occurs within a process zone on the order of $\lesssim$ 5 μm in diameter.

Previous work[2-5] had suggested that linear elastic fracture mechanics (LEFM) correlations of crack growth rate (da/dN) based on the cyclic stress intensity factor (ΔK) might be inappropriate as a driving force parameter for small cracks. This conclusion arose specifically from crack tip measurements which showed[6,7] that similitude (equivalent local crack tip plastic flow field for same ΔK) was not preserved for large and small fatigue cracks. The latter work demonstrated further that crack closure (shielding) was only one, nondominant factor in the growth of small cracks, and that the essence of the problem involved powerful microstructural effects. Thus, the specific objective of the program was to either discover a microstructurally-based alternative (to ΔK) crack driving force, or determine an analytical approach by means of which to introduce microstructural response directly into the LEFM driving force expression.

II. Summary of Program

The experimental research effort has focussed on characterization of the growth of small surface fatigue cracks in precipitation-hardened aluminum alloys, since their behavior is representative of that observed in many structural steels, titanium alloys, and nickel-base superalloys. Specimens were cycled and observed within a unique servocontrolled, hydraulic, in-situ SEM loading stage, permitting the determination of crack tip opening displacements, local plastic strain, and crack opening load/mode.[6-10] Selected area electron channeling was used[11,12] to determine the crystallographic orientation of grains containing microcracks, relative to the crack plane and the load axis. Finally, the very early stages of microcrack extension, in which the crack was immersed within a single grain, were characterized by scanning electron and TEM replica microscopy.[12] These observations were combined to develop physically valid microcrack growth models.[11-13] Principal experimental and theoretical results are summarized as follows (details are provided in the refereed publication list in Section III):

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*Superscripts refer to References.

1. Small fatigue cracks grow via the same microscopic extension mechanisms characteristic of large cracks.

2. However, local crack tip strains, local crack tip openings, (Figure 1) and average crack growth rates (Figure 2) for small cracks exceed those for large cracks, when correlated using ΔK.

3. Local crack tip strains, local crack tip openings (Figure 3), and average crack growth rates (Figure 4) for both large and small cracks correlate with $K^* = (E\Delta J)^{1/2}$, where ΔJ represents the cyclic J integral computed experimentally about a path inside the crack tip plastic zone, and E is the elastic modulus.

4. Unfortunately, this procedure, although providing both tremendous insight into the physics of the small crack problem and a valid driving force alternative to ΔK, is impractical for lifetime prediction, since it requires information obtainable only within a specialized laboratory setting (an SEM load-cycling stage).

5. When small cracks grow at rapid rates, their plastic zones lie within the bounds of individual grains, and the crack front interacts with relatively few ($\lesssim 10$) grains.

6. Thus, small and large cracks grow according to the same physical mechanism, but small ones grow within a metallurgical environment which resembles a single crystal.

7. By writing the stress intensity factor in terms of the Dugdale-Barenblatt formalism, it is possible to introduce into ΔK the local (single crystal) yield stress superimposed upon the average (polycrystalline) yield stress.

8. The resulting model, predicated on the notion of orientation-dependent microplastic grains, predicts quantitatively the entire range (Figure 5: arrest, retardation, "anomalous" rapid growth) of small fatigue crack behavior.

9. The model agrees with experimental data (Figure 6).

10. For the model to be valid, however, it requires that small cracks initiate within grains in which the Schmid factor approaches its maximum possible value (0.5).

11. Selected area electron diffraction experiments prove (Table I) that this is indeed the case.

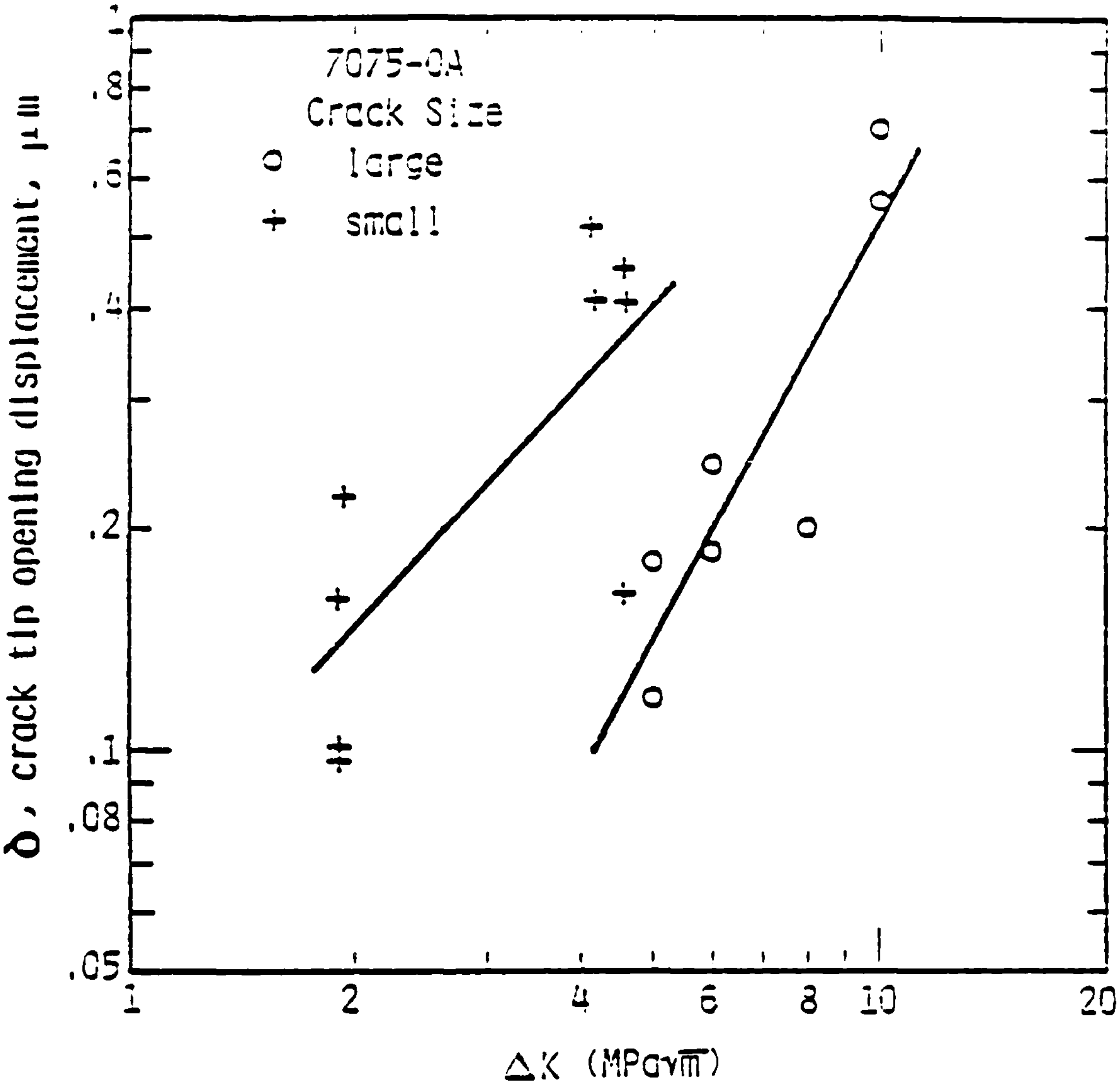

Figure 1. Comparison of crack tip opening displacements for large and small fatigue cracks in overaged 7075 aluminum alloy.

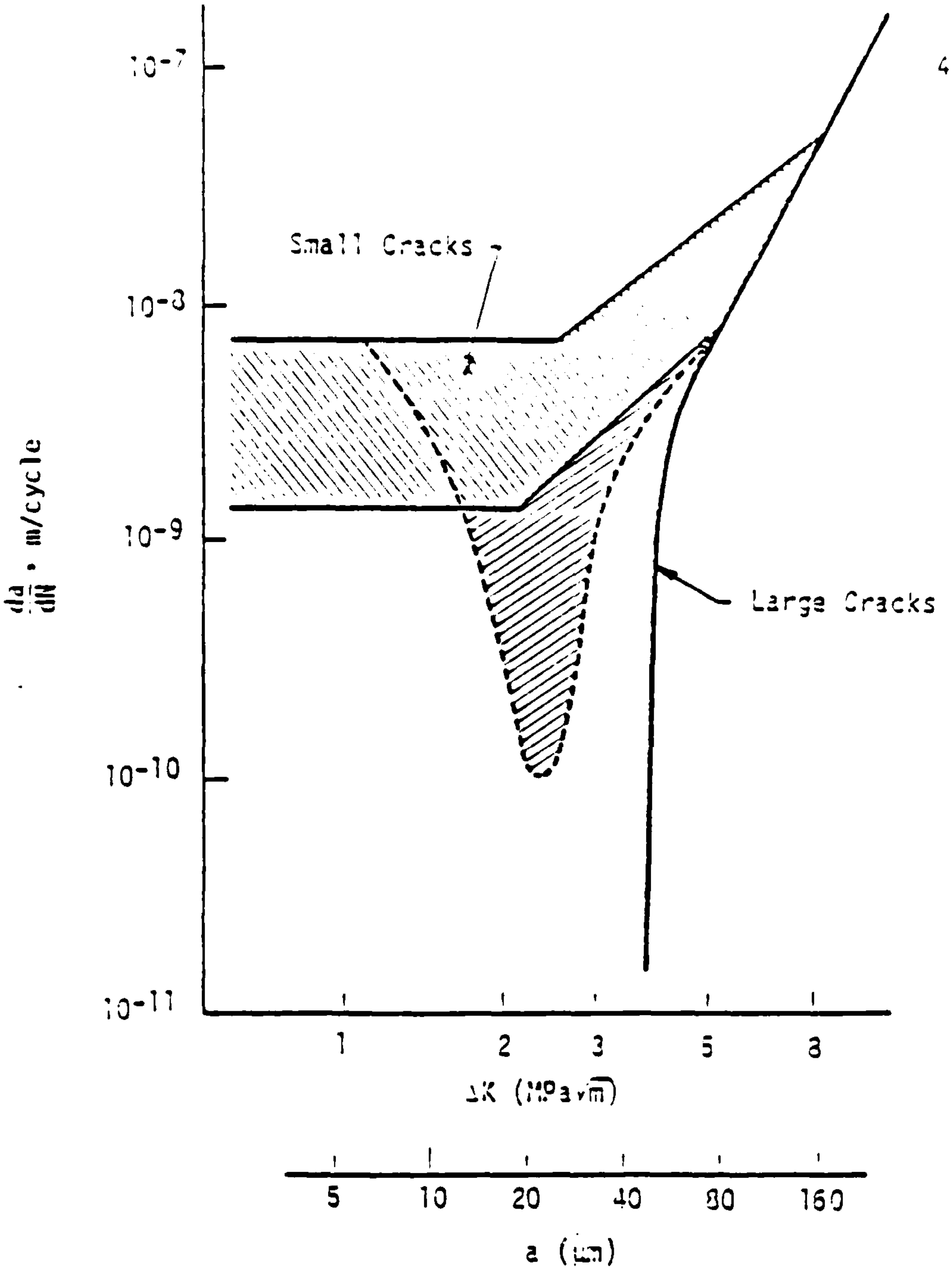

Figure 2. Small fatigue cracks in 7075 aluminum alloy tend to grow significantly faster than do large cracks at equivalent ΔK, and below the large crack threshold. Crack retardation and arrest observed in small cracks is indicated by the shaded region within the dashed envelope.

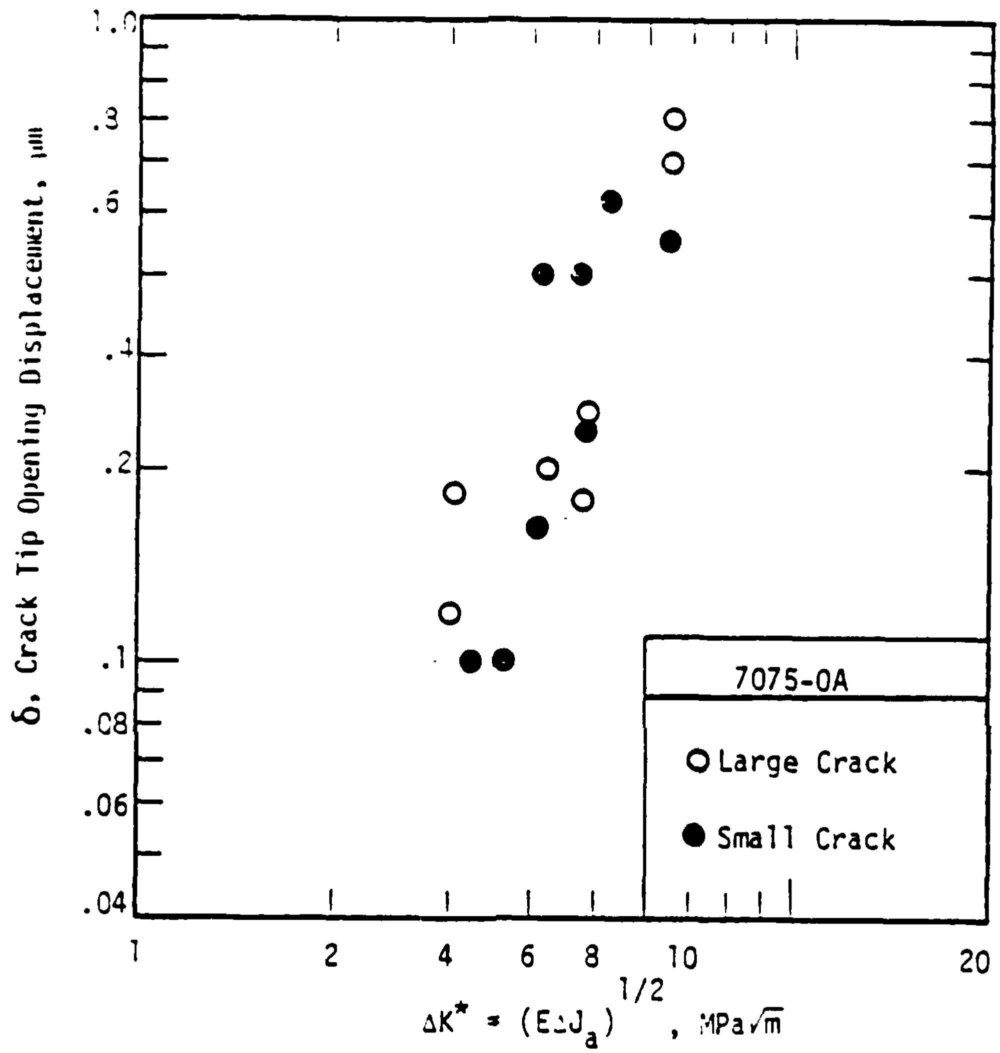

Figure 3. Correlation of crack tip opening displacements for large and small cracks using ΔK^* [$\Delta K^* = (E\Delta J_a)^{1/2}$] evaluated based on the average value of the local ΔJ integral, ΔJ_a, within the cyclic plastic zone.

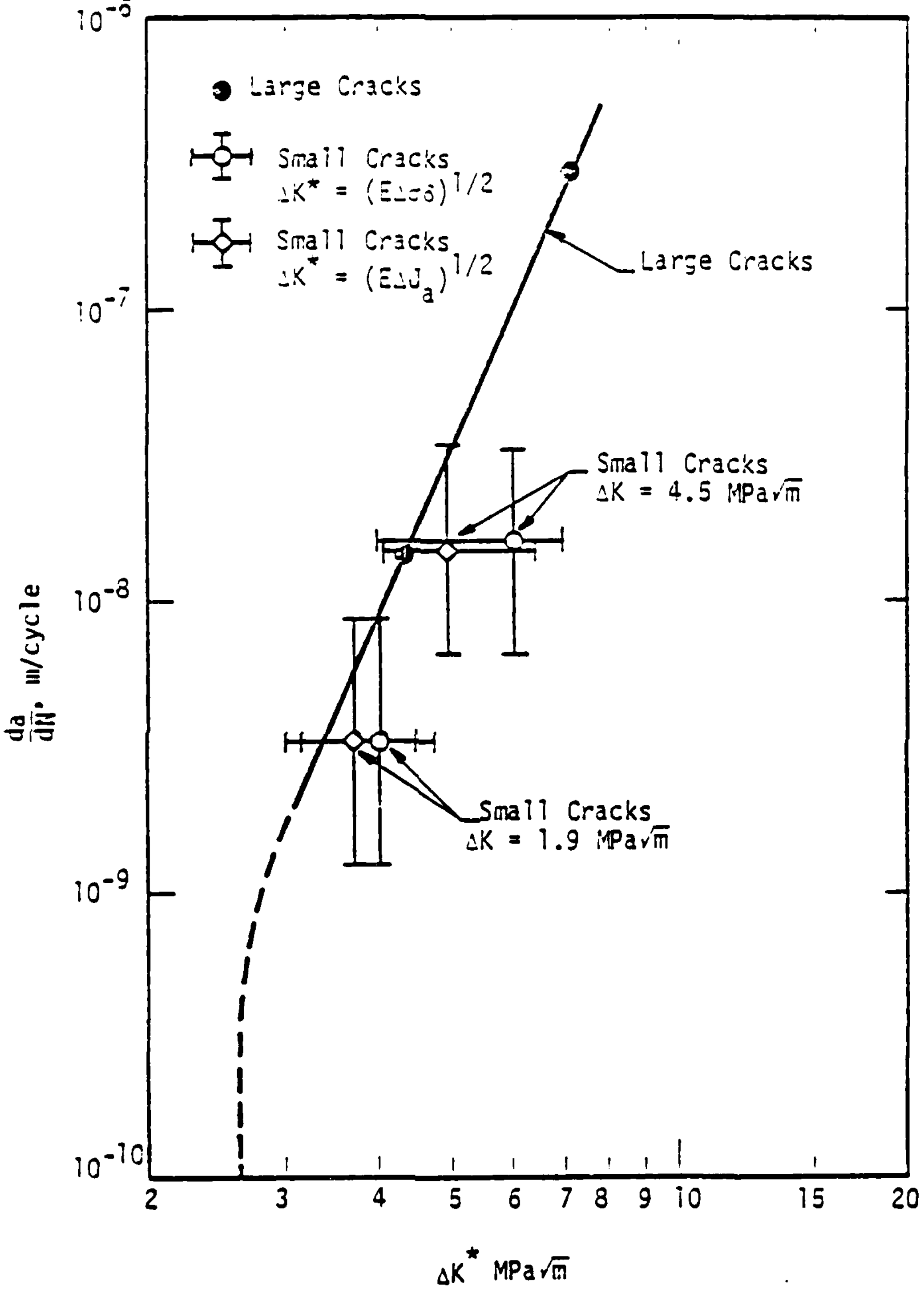

Figure 4. Correlation of crack growth rates of small and large cracks using ΔK^* evaluated based on the average local ΔJ-integral, ΔJ_a, or the crack tip opening displacement, δ.

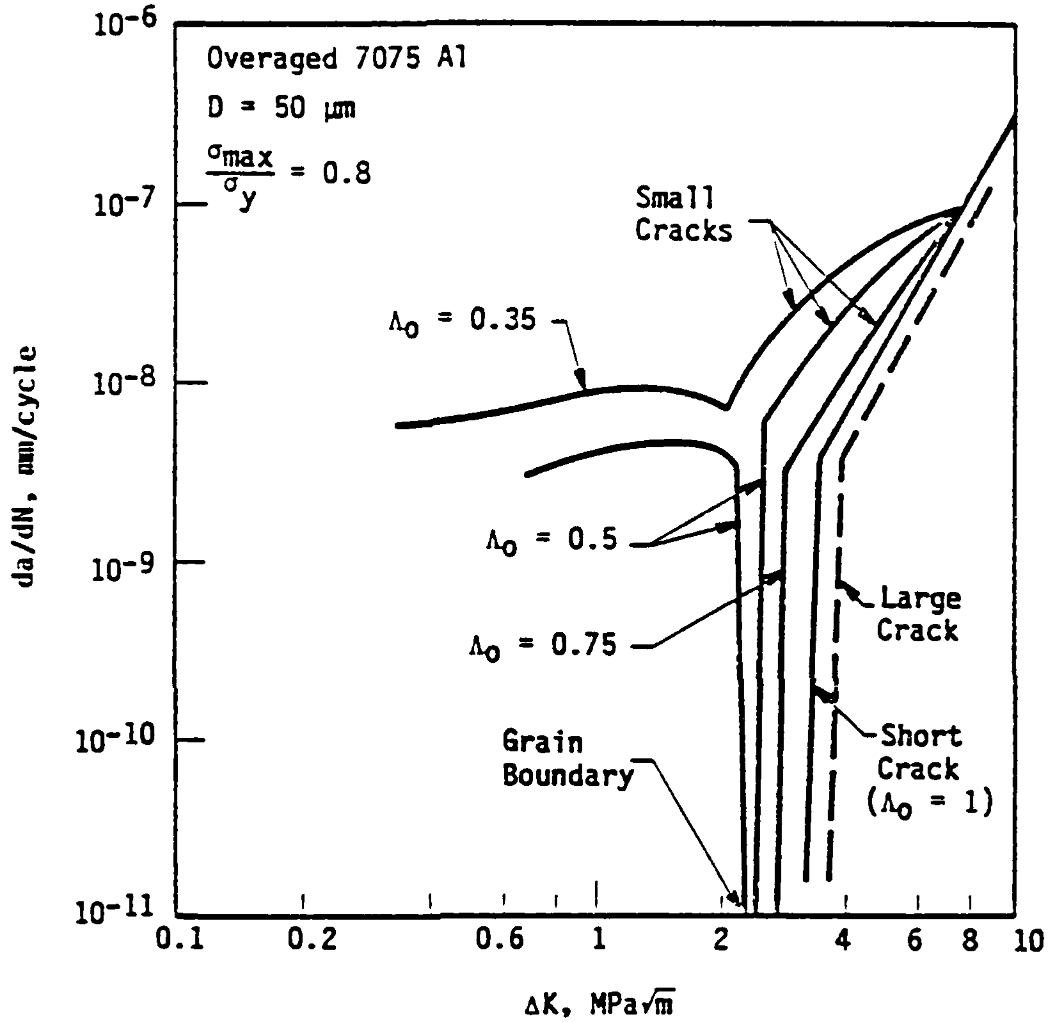

Figure 5. Predicted crack growth curves for small cracks propagating from a microplastic grain into elastic-plastic, contiguous grains; Λ_0 is defined as the ratio of the local resolved shear strength to the macroscopic polycrystalline yield strength.

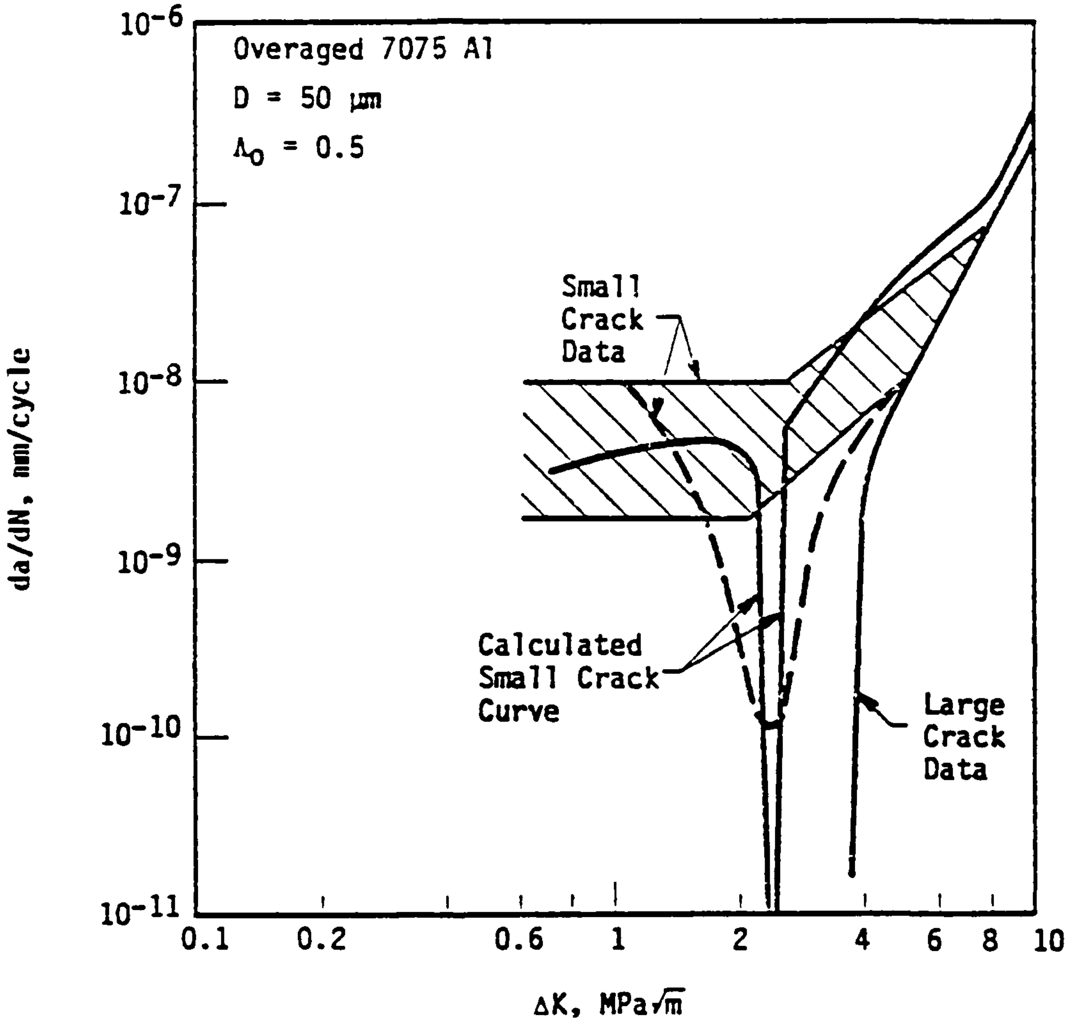

Figure 6. Comparison of calculated and experimental crack growth results of small cracks for overaged 7075 Al.

TABLE I

CRYSTALLOGRAPHIC INFLUENCE IN THE NUCLEATION AND GROWTH OF SURFACE MICROCRACKS IN 7075-T651 Al

CRACK	GRAIN	SCHMID FACTOR
1 (fatal)	A	0.489
2	A	0.489
3	A	0.489
4	B	0.482
5	C	0.437

12. The results indicate that for conservative lifetime prediction purposes, small crack behavior should be considered on a worst case basis, i.e., fastest possible growth within favorably oriented contiguous grains. Large crack data, especially threshold concepts, are invalid for small cracks, and can introduce large lifetime errors which increase dramatically as the initial size of a microcrack decreases (Figure 7).

III. List of Publications Under Current Contract

1. "The Influence of Crack Tip Plasticity in the Growth of Small Fatigue Cracks," by J. Lankford, D. L. Davidson, and K. S. Chan, Metallurgical Transactions, 15A, 1579, 1984.

2. "Near-Threshold Crack Tip Strain and Crack Opening for Large and Small Fatigue Cracks," by J. Lankford and D. L. Davidson, Concepts of Fatigue Crack Growth Threshold, The Metallurgical Society of AIME, New York, N.Y., ed. D. L. Davidson and S. Suresh, 447, 1984.

3. "The Influence of Microstructure in the Growth of Small Fatigue Cracks," by J. Lankford, Fatigue of Engineering Materials and Structures, 8, p. 161, 1985.

4. "Experimental Mechanics of Fatigue Crack Growth: The Effect of Crack Size," by D. L. Davidson and J. Lankford, Fundamentals of Deformation and Fracture, Edited by B. A. Bilby, K. J. Miller, and J. R. Willis, Cambridge University Press, Cambridge, England, 529, 1985.

5. "A Comparison of Crack Tip Field Parameters for Large and Small Cracks," by K. S. Chan, J. Lankford, and D. L. Davidson, Journal of Engineering Materials and Technology, 108, 206, 1986.

6. "Small Fatigue Cracks: A Statement of the Problem and Potential Solutions," by R. O. Ritchie and J. Lankford, Materials Science and Engineering, 84, 11, 1986.

7. "High Resolution Techniques for the Study of Small Fatigue Cracks," by D. L. Davidson and J. Lankford, Small Fatigue Cracks, ed. R. O. Ritchie and J. Lankford, TMS-AIME, Warrendale, PA, 455, 1986.

8. "The Role of Metallurgical Factors in Controlling the Growth of Small Fatigue Cracks," by J. Lankford and D. L. Davidson, Small Fatigue Cracks, ed. R. O. Ritchie and J. Lankford, TMS-AIME, Warrendale, PA, 51, 1986.

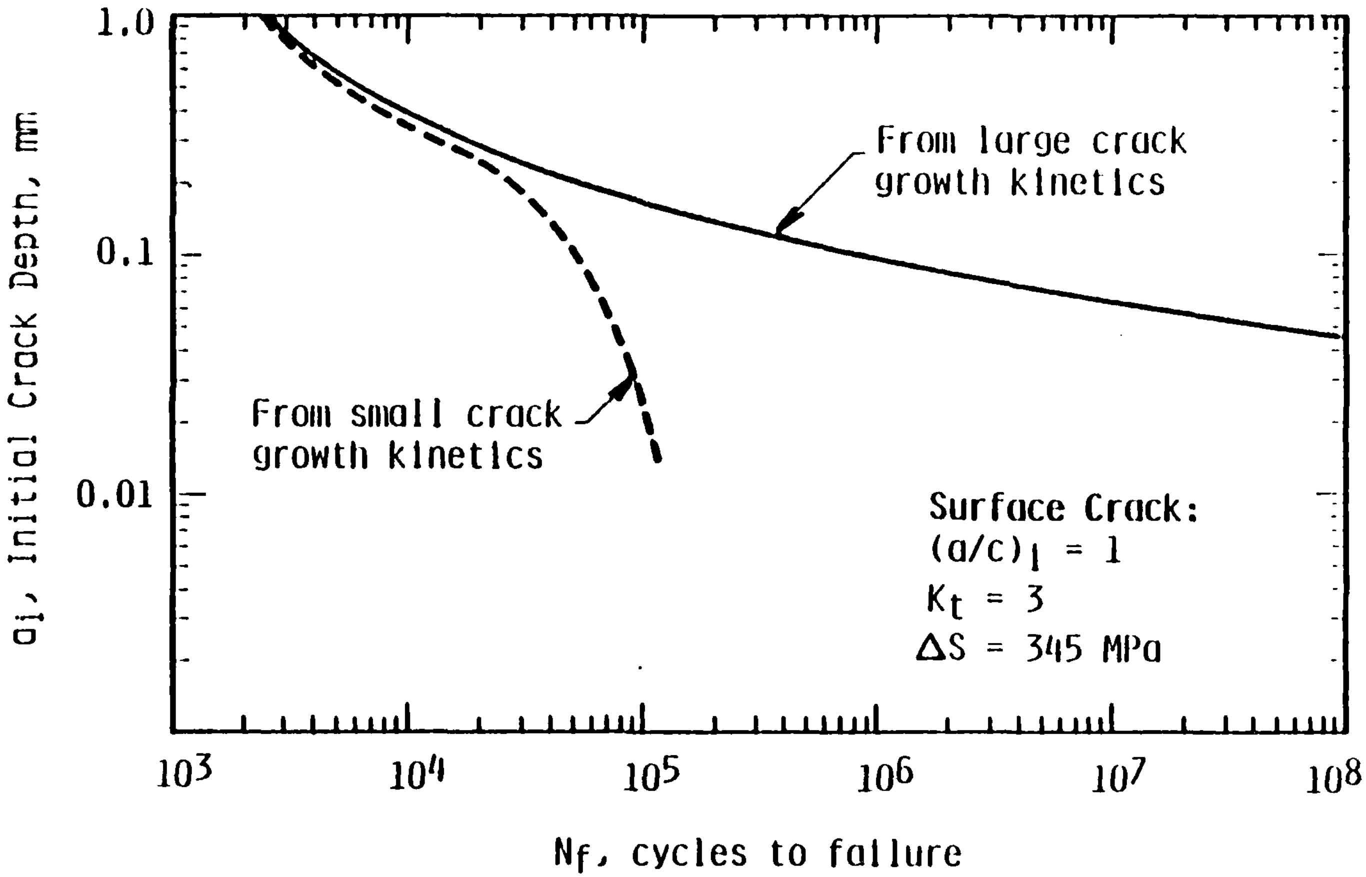

Figure 7. Influence of initial surface crack length on the predicted cyclic life of an Astroloy turbine disc based on large versus small crack growth kinetics.

9. "Overview of the Small Crack Problem," by R. O. Ritchie and J. Lankford, Samll Fatigue Cracks, ed. R. O. Ritchie and J. Lankford, TME-AIME, Warrendale, PA, 1, 1986.

10. "In Search of a Field Parameter to Characterize the Mechanical Driving Force for Small Cracks," by S. J. Hudak and K. S. Chan, Small Fatigue Cracks, ed. R. O. Ritchie and J. Lankford, TMS-AIME, Warrendale, PA, 1986, 379-405.

11. "Local Crack Tip Field Parameters for Large and Small Fatigue Cracks: Theory and Experiment," by K. S. Chan, Small Fatigue Cracks, ed. R. O. Ritchie and J. Lankford, TMS-AIME, Warrendale, PA, 1986, 407-425.

12. "Relevance of the Small Crack Problem to Lifetime Prediction in Gas Turbines," by J. Lankford and S. J. Hudak, Jr., International Journal of Fatigue, 9, 87, 1987.

13. "Role of Microstructural Dissimilitude in Fatigue and Fracture of Small Cracks," by K. S. Chan and J. Lankford, Acta Metallurgica (in press).

14. "The Micromechanisms of Small Fatigue Crack Growth and the Influence of Metallurgical Structure," by J. Lankford and D. L. Davidson, Fatigue 87, ed. E. A. Starke and R. O. Ritchie, Engineering Materials Advisory Services, Ltd., Cradley Heath, UK, 1987 (in press).

15. "Small and Large Fatigue Cracks in Aluminum Alloys," by D. L. Davidson, Acta Metallurgica (submitted).

16. "Micromechanics of Small Fatigue Cracks: A Model," by K. S. Chan, Fatigue 87, ed. E. A. Starke and R. O. Ritchie, Engineering Materials Advisory Services, Ltd., Cradley Heath, UK, 1987 (in press).

IV. Participating Scientific Personnel

1. Dr. James Lankford (Institute Scientist, Principal Investigator).
2. Dr. David L. Davidson (Institute Scientist)
3. Dr. Kwai S. Chan (Senior Research Engineer)
4. Dr. Stephen J. Hudak (Staff Scientist)
5. Mr. James F. Spencer (Senior Technician)
6. Mr. John B. Campbell (Senior Technician)

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10. D. L. Davidson and J. Lankford, Small Fatigue Cracks, ed. R. O. Ritchie and J. Lankford, TMS-AIME, Warrendale, PA, 1986, 455.

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12. J. Lankford and D. L. Davidson, Fatigue 87, ed. E. A. Starke and R. O. Ritchie, Engineering Materials Advisory Services, Ltd., Cradley Heath, UK, 1987 (in press).

13. K. S. Chan, J. Lankford, and D. L. Davidson, J. Eng. Mat. Tech., 108, 1986, 206.

VI. List of Illustrations

Figure 1. Comparison of crack tip opening displacements for large and small fatigue cracks in overaged 7075 aluminum alloy.

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